HOWE & FREY

LEVEL II

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CATASTROPHIC REACTION OF COMPARTMENTALIZED AMMUNITION - CAUSES AND PREVENTIVE MEASURES

PHILIP M. HOWE Ph.D
ROBERT B. FREY Ph.D
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MD 21005

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INTRODUCTION

While it is feasible to design a tank ammunition compartment which will survive the detonation of a single warhead, the design of a compartment which will survive the detonation of most or all of the warheads and which falls within the weight and space constraints imposed by the vehicle design is not currently possible; the detonation of 40 warheads (the planned complement) will destroy compartment and fighting vehicle. In previous research (1) we have shown that catastrophic reaction of munitions can occur under conditions much less strenuous than those required for classical shock initiation, which has been studied extensively for bare charges. These catastrophic reactions play an extremely important role in determining munition vulnerability, and in the rapid propagation of explosion through stacks of munitions. Typically, these catastrophic reactions take place in the 100-700 μsec time frame, consume essentially all of the explosive, and may appear to be detonations to the observor interested in assessing damage potential. To understand the mechanisms of initiation of these reactions, and to devise preventive techniques suitable for safe transportation and storage, and vulnerability reduction of armored fighting vehicles, we have undertaken analyses and a variety of experiments. Pertinent results are summarized in this paper.

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Interround Communication and the Role of the Casing

When a munition such as a 155mm artillery shell is detonated, nearby munitions are subjected to multiple fragment impacts, airblast, and severe loading from the explosive products. Initiation of the target munitions can occur as a result of a single, massive, high velocity fragment, as a result of multiple fragment impacts occurring nearly simultaneously, or as a result of the severe blast loading delivered by fragments and explosive products. One might conjecture that some measure of protection would be provided the target munitions by heavy walled casings, but it must be remembered that a heavy walled protective casing of a target round implies massive lethal fragments when such a round serves as the donor.

Because there is a variety of parameters which may affect interround communication, a series of experiments was performed to establish a data base and to provide insight with respect to the pertinent mechanisms. Munitions from the inventory were used rather than specially designed test fixtures, because the former would provide a much needed practical data base and because analysis had shown that the variations in geometry from munition to munition could be accounted for and would not weaken the validity of the results. Each experiment involved three munitions placed collinearly upon a 2.5 cm steel witness plate (see Figure 1). The two outer munitions served as targets for the center warhead which was deliberately detonated via primacord embedded within some C-4 plastic explosive which filled the fuze cavity. (In some cases, target warheads contained fuzes. However, fuze presence did not change threshold response, and there was no evidence in any experiment to indicate that the fuze contributed to reaction of the target warheads). The donor wall thickness, diameter, and explosive content, and acceptor wall thickness, diameter, and explosive content were varied. Data were obtained for munitions containing composition B ($60\%_w$ RDX, $40\%_w$ TNT) and composition A-3 (91% RDX 9% wax).

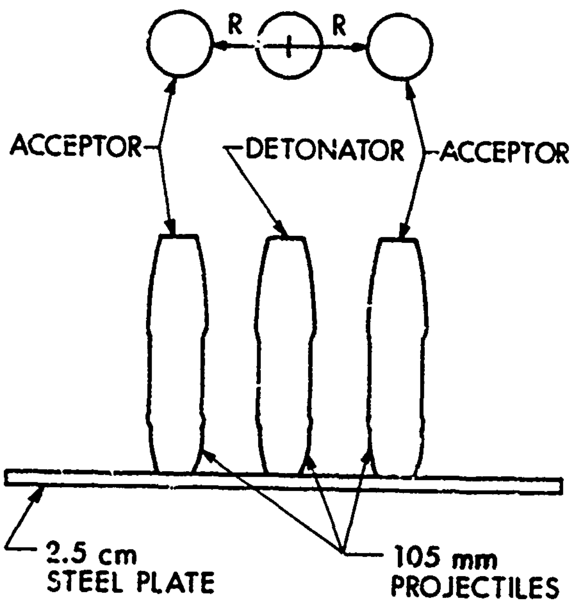

Figure 1. Schematic of typical test configuration for interround communication

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The condition of the acceptor warheads and the witness plate was examined after each experiment to determine acceptor response. When a donor was detonated in the design mode, it always perforated the witness plate and this was taken as a crude but effective indicator of acceptor detonation. For each type of warhead pair, the separation distance between rounds was varied in accordance with standard quantal response techniques (2) to determine the propagation threshold. Separate tests were performed on inert loaded projectiles placed at separation distances at which the acceptor detonated. This permitted determination of the level of damage which would lead to violent reaction or detonation of the acceptor warheads. At the violent reaction threshold, each inert-loaded acceptor was severely deformed and failure of the warhead casing occurred. This provided an important clue with respect to the mechanism by which violent reaction occurs within the acceptor. All the data are consistent with a mechanism involving

- casing deformation
- compression of the explosive, generation of cracks within the explosive
- failure of the casing
- rapid extrusion of explosive through cracks in casing, causing ignition and rapid spread of reaction through the cracked explosive, with resultant catastrophic explosion.

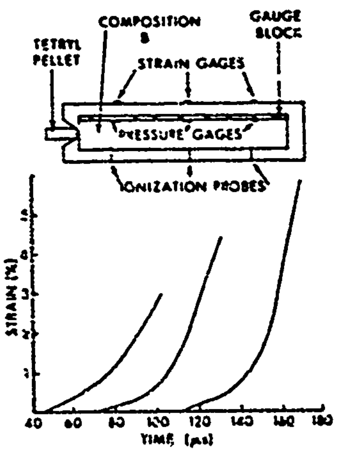

Figure 2. Schematic of apparatus used for mechanistic studies. Typical strain/time records at various gauge locations.

Additional experiments were conducted to explore some of the details of the initiation process. In one set of experiments, heavily confined composition B charges were fabricated, with internal manganin pressure gauges and externally mounted constantan strain gauges (see Figure 2). These charges were deliberately ignited, in order to permit observation of the development of violent reaction.

The detailed behavior of the charges was variable and strongly a function of geometry. Thus, for some experiments, a compression

wave propagated through the charge at a velocity of 2.0 - 2.5 mm/μsec. This wave was clearly not a shock, as the pressure gradient typically extended over a period of 10 - 30 μsec behind the wave front, to a peak pressure of 0.2 - 0.8 GPa. Generally speaking, strain records and stress records were similar. A plot of strain versus time at various gauge stations for such an experiment is shown in Figure 2. Ionization probes indicated reaction begins within a few microseconds of wave passage. Nonetheless, the pressures involved are too low to cause ignition by rapid compression of the explosive (3,4). (Note that, even with ignition, the reaction would not necessarily build up to violent reaction or detonation. In some instances, localized reaction occurs, and disrupts part of the charge without propagating to the rest.)

In other experiments, using larger diameter charges the pressure rose slowly but uniformly throughout the charge. After 200 - 600 μsec, a threshold was reached, at which point the pressure rose very rapidly and catastrophic reactions occurred. As in the previous experiments, the thresholds at various stations occurred sequentially and are associated with the arrival of a compression wave. In these latter experiments, the compression waves decayed as they propagated, and ionization probes responded erratically, indicating that low-level secondary ignition sources were developing at various locations. In both sets of experiments, large strains and strain rates were recorded coincident with the point at which the pressure transition points occurred.

At first we thought that charge deformation might be creating adiabatic shear bands which caused secondary ignition of the charge at points remote from the initial reaction. We analyzed the rate of temperature rise when two layers of explosive slip with respect to one another under pressure and with melting. The analysis indicates that sliding velocities of the order of $3X10^3$ cm/sec would be necessary for initiation at 0.1 GPa pressure. At lower sliding rates melting would suppress the temperature rise. In our experiments where the rate of shear deformation has been measured, such sliding velocities at shear bands could occur only if the shear bands were separated by distances of the order of a centimeter, which is unlikely. Therefore, it appears that the formation of shear bands does not explain the propagation of reaction in these experiments, although they could be responsible for the initiation of reaction in other circumstances.

An alternative explanation, consistent with the interround communication data and fragment impact data, is that homogeneous (on a macroscopic scale) deformation of the explosive does not cause secondary ignition, but that ignition results from casing failure and extrusion of the explosive into the cracks formed as the case opens.

An experiment was designed to test this hypothesis. It is shown schematically in Figure 3. Propellant was burned in the breech, thereby driving a plastic piston into the explosive, which was held in place by a deformable cylindrical container. The explosive was subjected to pressures and deformations similar to those of earlier experiments, but the deliberate ignition source was eliminated. In this experiment, ignition and violent reaction always occurred, but only after the metal case ruptured. We conclude that ignition and the development of violent reaction in confined charges is intimately connected with casing failure.

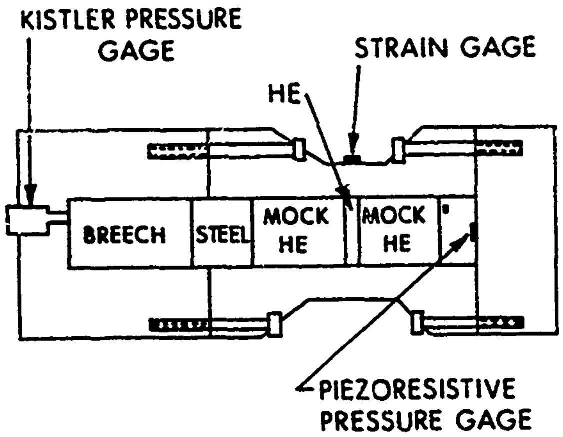

Figure 3. Apparatus used to show that ignition results from casing failure.

Huffington, in a parametric study of the response of thin shells to external blast loading, considered effects of geometry, loading, and material properties for fixed end cylinders subjected to a "frontal cosine" distribution of impulsive loading (3). The geometry is shown in Figure 4.

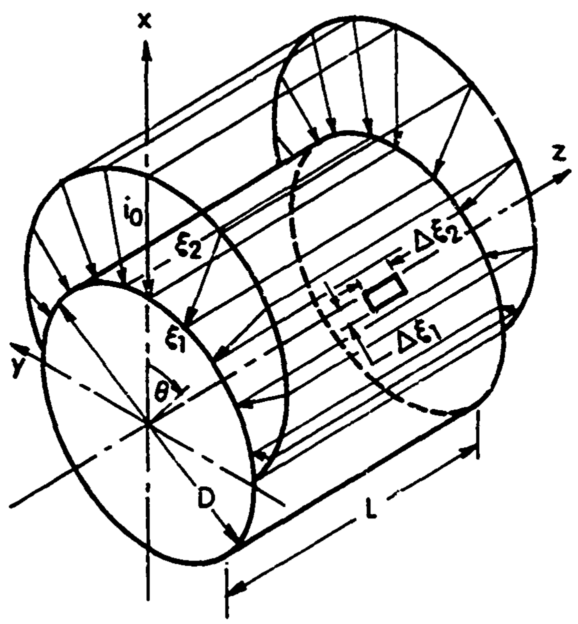

Figure 4. Frontal cosine impulsive loading for a fixed-ended cylinder (3).

The shells were considered to be thin (D/h <1) and Kirchhoff's hypothesis was applied (5). A mathematical formulation nonlinear in the equations of motion, the elasto-plastic stress strain relations, and the strain displacement relations was developed. The behavior of the solution was explored by varying non-dimensional ratios one

at a time, holding others constant. For complete details, the reader is referred to the original paper. Of special interest, however, is the fact that both maximum and residual deformation are strong functions of a scaled impulse density, $\frac{i\,C_o}{Eh}$, (where i is the impulse/area C_o the speed of sound in the casing, h the casing wall thickness, and E Young's modulus), and the fact that these functions depend only weakly on dimensionless ratios such as length/diameter, (L/D) and case thickness/diameter (h/D); (see Figure 5).

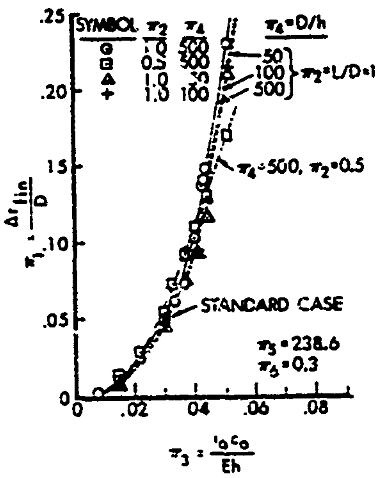

Figure 5. Casing response vs impulse intensity.

This is particularly important; it permits the identification of a critical deformation for casing failure with a unique value of the scaled impulse density delivered to the target, and the threshold inter-round communication distance can be obtained by equating the scaled impulse density to some critical value

$$\pi_3 = \frac{i\,C_o}{Eh} = \pi_{crit}.$$

This critical value must be obtained from experiment. For fragmenting munitions contained within typical arrays such as tank ammunition compartments or pallets, the fireball of the donor munition envelopes the vicinal munitions. Thus, both fragments and explosive products contribute to the impulse density delivered to the acceptors. We calculated values of the average areal fragment momentum according to the relation, applicable for cylindrical changes:

$$\frac{mV}{A} = \frac{\rho\,(r_o^2 - r_i^2)\,V}{2R}$$

where ρ is the donor casing material density

r_i is the donor casing inside radius

r_o is the donor casing external radius

v is the average fragment velocity, calculated using Gurney Formulae.

R is defined by Figure 1.

The total specific kinetic energy, E_{HE}, is given by

$$E_{HE} = \frac{\overline{V}_{HE}^{\,2}}{2}$$

where $\overline{V}$ is the average product speed. E_{HE} is proportional to the Gurney energy, E*, so

$$\overline{V} \; \alpha \sqrt{2E^*}$$

and the scaled areal impulse ratio delivered by the explosive varies according to the relation

$$\frac{i\, C_o}{Eh} \; \alpha \; \frac{r_i^{\,2}\sqrt{2E^*}}{RhE}$$

Thus, if the explosive products control the deformation, the critical deformation criterion implies that

$$\frac{R_o^{\,2}}{R}\,\frac{\sqrt{2E^*}}{h} = \text{constant, or } \frac{r_i^{\,2}\sqrt{2E^*}}{h} \text{ vs R be linear.}$$

(The parameters C_o, ρ, and E, which don't vary in our experiments are suppressed). The data are plotted in Figure 6 and pertinent calculated parameters are reported in Table 1. A regression analysis of R into each of the parameters in Table 1 was made and the correlation coefficients are shown in Table 2. Note that R correlates very well with i/h, but does not correlate significantly with any of the fragment parameters: in interround communication between fragmenting munitions, the development of violent reaction is independent of fragment parameters. That the fragments contribute to the initiation process can be seen by comparing the 50% separation distance for a 105mm HEP acceptor and a bare charge donor of the

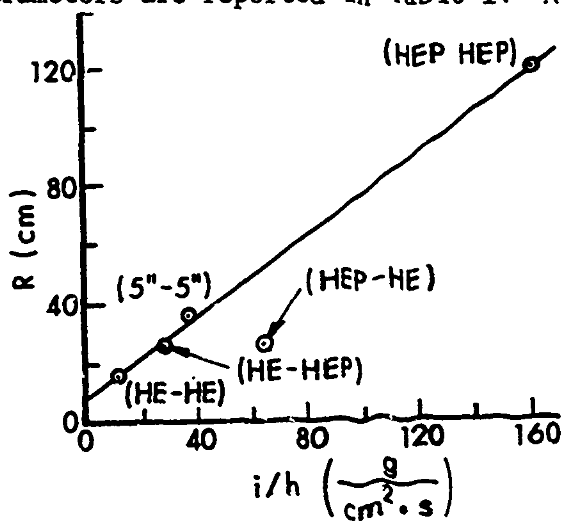

Figure 6. The dependence of R upon scaled impulse intensity.

Table I. Measured and Calculated Results for Interround Communication

Donor	Acceptor	R (cm)	E_f $(g/s^2)\times10^{10}$ Fragment Areal Kinetic Energy	P_f $(g/m\cdot s)\times10^{7}$ Fragment Areal Momentum	$\dot{i}$ $(g/m\cdot s)\times10^{5}$ Total Areal Momentum	h (cm) Acceptor Wall Thickness
M1 HE	M1 HE	17.8	5.6	3.6	11.3	1.02
M1 HE	M393A2	25 ± 5	5.6	3.6	11.3	0.4
M393A2	M1 HE	26	5.7	2.4	64.5	1.02
5" 54	5" 54	35.4	3.7	4.1	60.6	1.65
M393A2	M393A2	119.3	5.7	2.4	64.5	0.4

Table II. Correlation Coefficients for Regression of R onto Various Parameters

	R	E_f	P_f	i	E_f/h	P_f/h	i/h
R	1	0.158	-0.548	0.524	0.557	0.227	0.960

same geometry and explosive content. The threshold for the HEP donor was 119.5 cm, that for the bare charge donor was 8.7 cm. The apparent ambiguity can be resolved by noting that the initiation of violent reaction requires casing failure and the explosive to be under compression when the casing fails. Casing failure is greatly facilitated by fragment impact, which induces high stresses in the casing, causing incipient spall. Compression of the explosive is determined by the deformation of the casing, however, and the deformation is proportional to the impulse, as shown earlier.

The Vulnerability of Cased Munitions to Impact by Single Fragments

The situation discussed above would change with increasing fragment mass and velocity; eventually an individual fragment would have sufficient areal impulse to reach the critical deformation to cause casing failure. Such is the case for threshold data from gun firings where there is no loading from explosive products and where the response of the target is to impact by single fragments. Reeves' data (6) covered fragment masses from 1.94 gm to 15.55 gm, impacting against composition B loaded 105mm HE warheads. We sponsored acquisition of additional data for identical targets, with fragments ranging from 75 gm to 300 gm. All fragments were steel, right circular cylinders, with L/D = 1. The response of the targets was inferred from post-firing examination of a 2.5 cm steel witness plate, and from recovery of target fragments. The criterion for a violent reaction was perforation of the witness plate. All data were obtained using

a standard quantal response technique (2). The data are plotted in Figure 7, together with Reeves' data. The fact that both sets of data fall upon the same curve is reassuring, and indicates that no experimental artifacts have been introduced because of different lots of munitions and different experimentors.

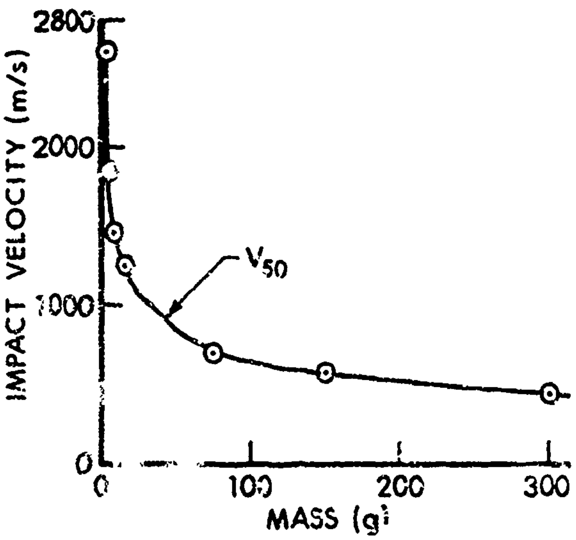

Figure 7. Threshold initiation (50%) for fragment impact of 105mm shell.

It is reasonable to expect that the fragment impact initiation of violent reaction in confined targets will obey the same mechanism as does interround communication. If so, the criterion for initiation of violent reaction is that a critical areal impulse/target casing thickness ratio be exceeded. Thus, we have for the 50% threshold locus of mass versus impact velocity, $\frac{mV}{Ah}$ = constant = $\rho \frac{LV}{h}$ where m is the fragment mass, V its impact velocity, A its area, L its length, and h the target casing thickness. Geometric similarily requires that L be proportional to the fragment radius. In particular, for the L/D = 1 fragments used here,

$$\frac{mV}{Ah} = \frac{2\rho\ rV}{h}$$

Since

$$r = \frac{m}{2\rho\pi}^{1/3}$$

the criterion becomes

$$\frac{m^{1/3}V}{h} = \text{constant}.$$

The data of Figure 7 are replotted in Figure 8 (circles). The solid curve is a straight line with a slope of -3. Note that the fit is good over a three decade change in mass. This provides very strong support for a mechanism which leads to an areal impulse criterion for initiation of violent reaction.

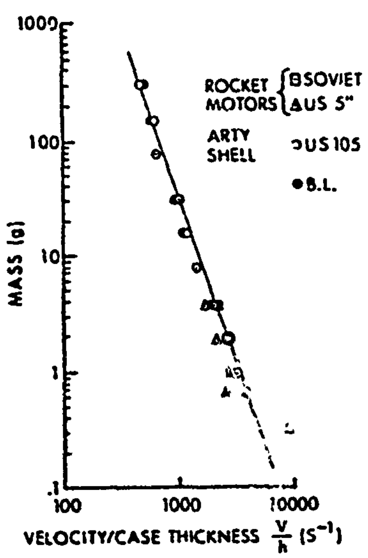

Figure 8. Comparison of initiation thresholds for rockets and shell, ballistic limit of shell.

Two corollaries follow from the above results: First, if the condition for initiation of violent reaction is that sufficient deformation of the casing occur to cause failure, i.e., crack generation, then the threshold for initiation should lie very close to the ballistic limit for the casing. To check this, firings against wax filled 105mm shell were conducted using 30 gm, 150 gm, and 300 gm L/D = 1 steel, cylindrical fragments. Some firings of fragments with masses of 3.87 g and 15.45g reported by Reeves (6) are included, also.

The data are shown in Figure 8, where the solid circles represent the average of the highest impact velocity at which no perforation of the casing was obtained and the lowest velocity at which perforation occurred. As can be seen, the conditions for initiation and the ballistic limit are nearly coincident.

The second corollary is that, if the condition for initiation is essentially that casing failure occur, then that condition would apply to different explosives systems, provided that the explosive is not very insensitive (a very insensitive explosive could cause the initiation to depend upon explosive parameters, rather than casing parameters). Some fragment impact data for the US 5" rocket motor and 122mm Soviet rocket motor from (7) are shown in Figure 8. Note that the data are coincident with the 105mm M1 data, in spite of major differences in composition of the filler. The compositions of the rocket motor propellant and the explosive fill are shown in Table 3.

Table III. Chemical Composition

Munition	Composition	Principal Ingredients
105mm M1 HE	B	60% RDX, 40% TNT
105mm M393 HEP	A-3	91% RDX, 9% Wax
5" MK 10 Mod 7 Rocket	double base prop.	51.4% Nitrocellulose, 42.9% Nitroglycerine, 3% Diethylphthalate
122mm Soviet Rocket	double base	(Composition Classified)
Navy 5" 54	A-3	91% RDX, 9% Wax

It is apparent that, at least for those systems for which data exist, the initiation of violent reaction by fragment impact is independent of the filler and is determined by the response of the casing.

Remedial Techniques

An understanding of the mechanism of initiation permits development of techniques which prevent or reduce the frequency of violent reactions resulting from fragment impacts and the detonation of nearby warheads. For munitions in the inventory, protective shields can be developed which reduce the stress levels and stress gradients experienced by the target casings, thus reducing the probability of casing failure. Elementary considerations in shock physics indicate that the best shields are those composed of materials with low shock impedances. The presence of a low shock impedance material between the impacting fragments and the casing causes a more gradual buildup of pressure in the casing and allows more time for rarefactions to reduce the peak stress. Thus, materials such as polyvinyl chloride, foamed metal, etc. should make good shields.

Based on this reasoning, shields were designed to prevent interround communication between 105mm M 456 HEAT warheads contained in a tank ammunition compartment. The effectiveness of the shields relied upon prevention of direct impacts by fragments upon warhead casings and reduction of the shock wave strength experienced by casing and explosive. A series of tests involving two warheads and a single shield per test demonstrated that a 5cm x 5cm x 40cm polyvinyl chloride bar effectively prevented reaction of the acceptors. Thus, in fifteen tests, not a single acceptor warhead detonated, exploded, or showed any evidence of reaction. For these tests, the wall to wall warhead separation was 5 cm. Three further tests were conducted to assess the effectiveness of the shields in a simulated tank ammunition compartment. The compartment geometry, wall thicknesses, interround spacing, etc., closely replicated designs currently under consideration

for the XM1 tank. A schematic of the setup is shown in Figure 9. One warhead in each test was deliberately detonated by attacking it with Rockeye shaped charge. In each test, only the deliberately detonated warhead reacted. Results of tests and design information have been provided the project manager, for incorporation into the XM1 tank.

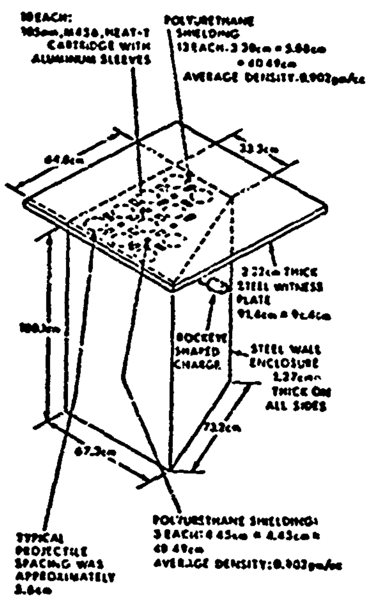

Figure 9. Mockup of tank compartment for confinement effects.

Another, complementary approach can be applied to new warheads entering the inventory. Ignition occurs when the casing fails, and is believed to be caused by the rapid extrusion of the explosive through casing cracks. If this is so, the ignition threshold could be raised by lining the warhead with a thin layer of a pliable polymeric material, which would act as a buffer between explosive and metal interface, during extrusion. (Experiments have shown that ignition occurs more readily as a result of metal- explosive friction than explosive-plastic or explosive-explosive interactions.) To test this hypothesis, 105mm M1 casings were lined with a 3mm coating of cellulose acetate butyrate. The coating thickness was chosen somewhat arbitarily and does not represent a minimum effective thickness. (Note, however, that 3mm is much too thin to provide significant shock attenuation - if shock ignition is the mechanism, the coating will be ineffectual.) Firings were conducted against the polymeric lined munitions with 8 gm steel fragments. The 50% threshold for such a fragment against an unprotected munition is 1470 m/s (4823 f/s). With the lined munitions, no evidence of reaction was obtained at impact velocities of 1740 m/s (5700 f/s), although this is well beyond the ballistic limit of the casing, and perforation occurred. Mild burning reactions were obtained at higher velocities. Even at impact velocities of nearly 2000 m/s (6500 f/s) the warheads did not react with sufficient violence to split open the casings.

SUMMARY AND CONCLUSIONS

Experiments are reported which were conducted to determine the interactions which occur between vicinal munitions. These experiments provided a data base we needed to address mass detonation issues and were designed to provide mechanistic information. Available theory and analysis provided a criterion for initiation, based upon an assumption about the mechanism. The initiation criterion permitted description of the threshold conditions for interround communication. In addition, it was found that, although the fragments participated in interround communication, the process was insensitive to donor fragment parameters, contrary to expectation.

Single fragment impact data was obtained against heavily confined targets. The data base was extended over that available in the literature so that the masses for impacting fragments ranged from 2 to 300 gms. The initiation criterion developed for interround communication was tested against single fragment impact initiation and shown to apply over three decades change in mass, the entire range for which data are available. Both the interround communication data and the single fragment impact data were shown to be consistent with a mechanism which involved deformation of the casing, compression of the explosive, failure of the casing, rapid extrusion of the explosive into cracks, causing ignition, and spread of reaction. Failure of the casing was found to be the critical step, and the initiation criterion was identified with the ballistic limit of the casing.

Since the rupture of the casing controlled the initiation process, the model should be applicable to other systems with similar geometries, but not necessarily similar chemical compositions. This hypothesis was tested against the US 5" MK 10 mod 7 rocket motor and the USSR 122mm rocket motor. Within the accuracy of the data, the initiation criterion applied equally well to these two systems as for the composition B targets for which it was developed.

Additional experiments were conducted to verify the hypothesis that initiation resulted from rupture of the casing and extrusion of the explosive into cracks. Constantan strain gauges and manganin pressure gauges were used to monitor the response of casing and explosive to various stimuli. It was found that catastrophic reaction resulted immediately after casing failure, given a deliberate ignition source. If the samples were not deliberately ignited, but were subjected to rapid deformation, ignition occurred when rupture occurred, with subsequent violent reaction.

Understanding of the mechanism was used to develop remedial techniques. The use of low shock impedance materials to prevent casing fracture was explored and a technique which prevented any inter-round propagation in compartmentalized tank HEAT ammunition was developed. Design information was provided to the XM1 project manager, for incorporation into the new tank.

A technique was developed and tested applicable to munitions entering the inventroy. This technique isolates the explosive from the casing and greatly improves the response of the munition to fragment impact.

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